Earth Surface Processes and Landforms
Earth Surf. Process. Landforms **24**, 1039–1054 (1999)

THE ROLE OF DEBRIS SUPPLY CONDITIONS IN PREDICTING DEBRIS FLOW ACTIVITY

MICHAEL J. BOVIS[1]* AND MATTHIAS JAKOB[2]
[1]*Geography Department, University of British Columbia, Vancouver, BC, V6T 1Z2, Canada*
[2]*EBA Engineering Consultants Ltd, 550–1100 Melville St, Vancouver, BC, V6E 4A6, Canada*

Received 13 July 1998; Revised 6 April 1999; Accepted 12 May 1999

ABSTRACT

Debris flow frequency and magnitude were determined for 33 basins in southwest British Columbia. Basins were first classified as either weathering-limited or transport-limited using a discriminant function based on debris-contributing area, an area-weighted terrain stability number, and drainage density. Multiple regression was used to predict magnitude, peak discharge, frequency and activity (frequency times magnitude) within each group of basins. Model performance was improved by stratifying the total sample of debris flow basins into weathering-and transport-limited groups. Explained variance increased by an average of 15 per cent in the transport-limited sample, indicating that sediment supply conditions in the more active basins are fundamental in predicting debris flow activity. An independent test of the regression models with 11 basins yielded generally good results for debris flow magnitude and peak discharge. Prediction of debris flow frequency proved problematical in weathering-limited basins. The methods developed here provide estimates of debris flow attributes in basins for which few data on past events are available. Copyright © 1999 John Wiley & Sons, Ltd.

KEY WORDS: debris flow; magnitude; frequency; terrain analysis; multiple regression; discriminant analysis; British Columbia

INTRODUCTION

Debris flow is a dominant mass movement process in the Coast Mountains of British Columbia and constitutes a significant natural hazard (Evans and Savigny, 1994). Although recognized as a frequently occurring and destructive phenomenon, relatively few studies have considered the magnitude–frequency aspects of this process in comparison with the large number of works on debris flow rheology and dynamics (summarized in Iverson, 1997). The relatively small number of magnitude–frequency studies also contrasts sharply with the situation in analytical hydrology and fluvial hydraulics, where magnitude–frequency relations have long formed a basis for engineering design. In debris flow studies, knowledge of event frequency and magnitude provides a rational basis for both hazard zonation and the design of mitigative structures. Such studies also provide estimates of the geomorphic work done by debris flows, and consequently are of value in the calibration of landscape evolution models.

Despite the practical and theoretical utility of magnitude–frequency studies, there are serious obstacles to obtaining such data. Often there is a lack of dating control for prehistoric events because of logging and other land disturbances, as well as a paucity of eye-witness accounts. Fluvial erosion of debris flow deposits prevents accurate volume estimates for any but the most recent events. In addition, the time series of debris flow events is usually incomplete since recent large events tend to obliterate depositional evidence of earlier, smaller flows. The debris flow time series is therefore notably censored for high-frequency, low-magnitude events. To work around this difficulty, previous studies have attempted to use morphometric variables to predict frequency and magnitude (Table I). From these and other studies it is known that debris flow

* Correspondence to: Dr M. J. Bovis, Geography Department, University of British Columbia, Vancouver, British Columbia, V6T 1Z2, Canada. E-mail: mbovis@geog.ubc.ca
Contract/grant sponsor: Natural Sciences and Engineering Council of Canada
Contract/grant sponsor: Gottlieb Daimler und Karl Benz Stiftung

CCC 0197-9337/99/111039–16 $17.50

Table I. Previous studies of morphometric controls of debris flow frequency and magnitude

Authors	Criterion variables	Predictor variables
Hampel (1977)	Magnitude	Basin area, fan slope
Ikeya (1981)	Magnitude	Channel length and width
Takahashi (1981)	Area-normalized magnitude	Basin area
Ikeya and Mizuyama (1982)	Magnitude	Channel length
Mizuyama (1982)	Area-normalized magnitude	Basin area
Kronfellner-Kraus (1983)	Magnitude	Mean slope, basin area
Thurber (1983)	Magnitude	Basin area, channel length
Hungr *et al.* (1984)	Magnitude	Basin area, channel length
VanDine (1985)	Magnitude	Basin area
Ellen and Mark (1993)	Frequency	Slope
Johnson *et al.* (1990)	Frequency and magnitude	Hypsometry, relief ratio, fire frequency

magnitude and frequency are functions of both hydroclimatic events (Keefer *et al.*, 1987; Church and Miles, 1987), as well as terrain variables (Hungr *et al.*, 1984; Jackson *et al.*, 1987; Cannon and Ellen, 1988; Jakob and Bovis, 1996). However, relatively little progress has been made in quantifying these factors in predictive models because of the climatic and terrain complexity of mountain areas. For these reasons, there are poor correlations between rainfall intensity and amount and the magnitude of resultant debris flows, even though precipitation intensity–duration envelopes have been developed for debris flow initiation (Caine, 1980). Bivariate regressions have proved useful in assigning limiting envelopes for debris flow magnitude, and some studies have reported a channel yield rate ($m^3\ m^{-1}$) by dividing event volume by travelled channel distance (Hungr *et al.*, 1984; Fannin and Rollerson, 1993; Jakob *et al.*, 1997).

Since magnitude is determined more by the volume of material entrained along the channel than by the volume of the initiating event (Swanston and Swanson, 1976; Fannin and Rollerson, 1993), channels must be recharged with material before a large debris flow can reoccur. Event frequency and magnitude are therefore controlled not only by local exceedence of a climatic threshold but also by factors such as terrain instability and ruggedness, which control debris supply and channel recharge rate.

Although sediment supply and channel recharge rate are important factors controlling debris flow activity, these aspects have received little attention to date. In this study we address these aspects by using basin morphometry, and variables describing debris supply conditions, to predict debris flow attributes. The approach is based on methods described earlier by Jakob and Bovis (1996). Basins are divided into two groups using multivariate discriminant analysis: (a) transport-limited basins, in which an almost unlimited amount of sediment is available to feed debris flows; (b) weathering-limited basins, in which sediment supply and channel recharge rates are lower, and a substantial time period must elapse before the next debris flow is possible. Having classified the basins according to sediment supply conditions, multiple regression is used to predict debris flow attributes in each group. Regression equations are then tested with an independent sample of 11 basins whose recent debris flow histories are known. The main focus of the paper is to demonstrate that stratification of basins according to debris supply conditions significantly improves the predictive power of such regression models.

STUDY AREA

Site selection criteria

Thirty-three basins were selected within the rugged southern Coast Mountains region of southwestern British Columbia (Figure 1). Basins were chosen primarily for the length of their debris flow records and for the quality of the evidence of debris flow volume, peak discharge and frequency. The requirement of an adequate record of debris flow events favoured the selection of relatively active debris flow basins. This bias in sampling is defended on the grounds that the most active basins present the greatest hazards. A second factor

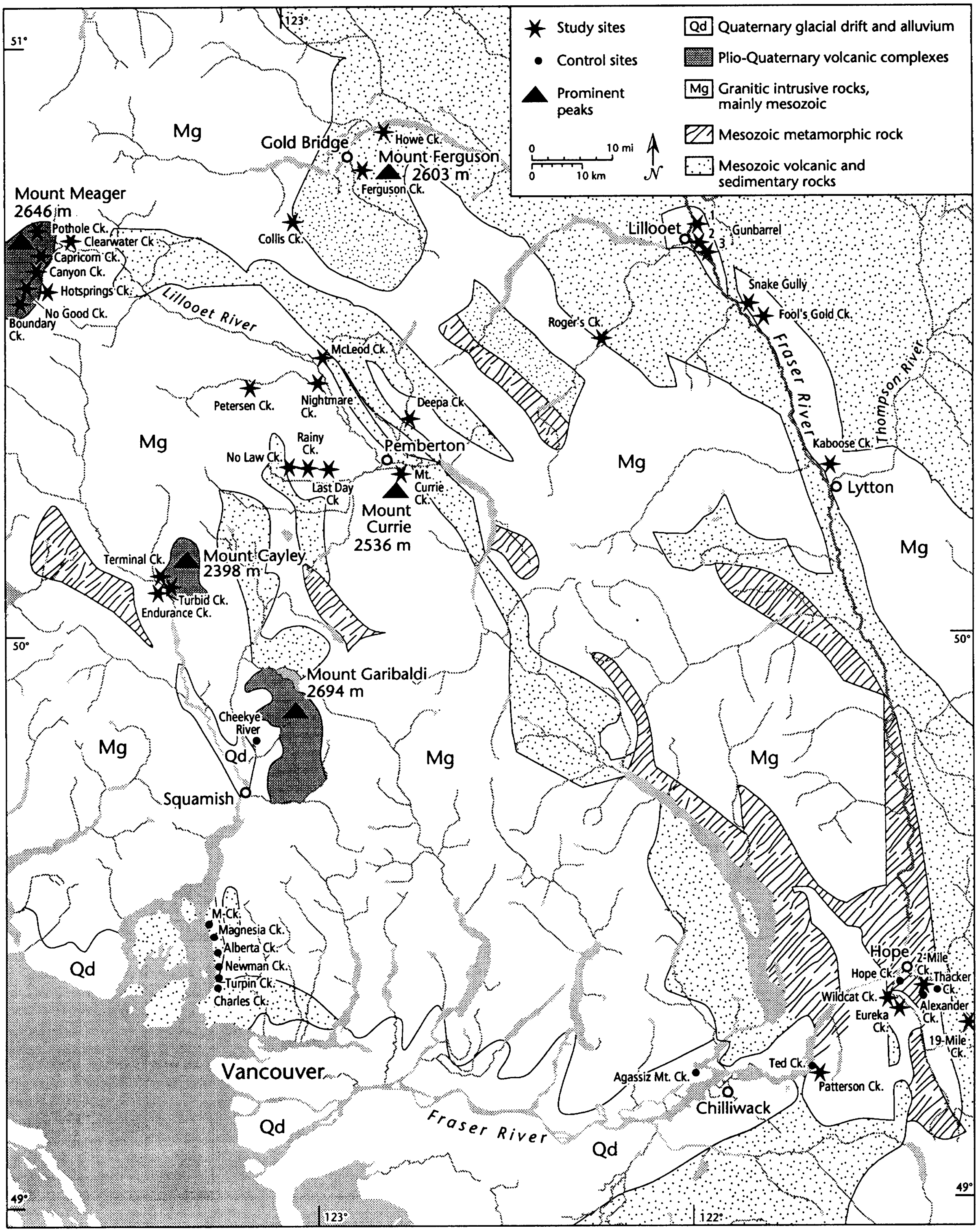

Figure 1. Generalized bedrock geology and locations of debris flow basins (Geology based on Monger and Journeay, 1994)

considered in basin selection was geological diversity, to ensure a region-wide applicability of findings. A third factor was absence of significant logging influences. Although the low-gradient fans of several of our basins have been logged within the past 30 years, the channels and adjacent slopes in the upper basin areas where debris flows are typically triggered are unlogged. The phenomena described here are therefore indicative of natural debris flow conditions.

Physiography and climate

The 25 000 km^2 study area straddles the Squamish, Lillooet, Bridge and Fraser river basins. Most of the study basins are located within the Coast Plutonic Complex, underlain by Mesozoic granitic and dioritic rocks (Monger, 1994). Geological contrast with intrusive rocks is provided by basins underlain by unstable Plio-Quaternary volcanic materials, such as occur at Mount Cayley and Mount Meager. In addition, several basins were located east of the Fraser River Fault system to sample a relatively weak assemblage of Cretaceous sedimentary and volcanic rocks. The bedrock of the study basins is thus representative of most of the rock types found on the southwestern mainland of British Columbia.

Quaternary glaciations have strongly influenced geomorphic conditions in the Coast Mountains (Ryder, 1981), and continue to influence debris flow events. High-relief alpine glacial landforms, carved into jointed and foliated rocks, exhibit a wide range of rock instability processes including rock slide, rock avalanche and rock toppling. In many cases, rock slope instability directly feeds debris to steep channels and triggers many debris flows. A second major debris source is unconsolidated Quaternary glacial drift and colluvium. Chronic ravelling of these materials is an important mechanism for the recharge of debris flow channels, and many debris flows are triggered by debris slides initiating in glacial drift or colluvium.

Climate and hydrologic conditions vary greatly across the study area between the perhumid western and the subhumid eastern flank of the Coast Mountains. The Howe Sound–Whistler–Pemberton corridor, north of Vancouver, has a winter precipitation maximum with annual totals ranging from 1100 mm at sea level to well over 3000 mm above 2000 m. Most debris flows are triggered by heavy rainfall or rain-on-snow events in the period October–December. By contrast, the eastern flank of the Coast Mountains, and the middle Fraser Valley between Lytton and Lillooet (Figure 1), lie in a rainshadow area having a summer maximum of precipitation and annual totals of 400–800 mm, increasing with elevation. Debris flows typically occur during rain-on-snow in spring and, in contrast to the coastal belt, many events are triggered by summer thunderstorms.

Debris flow terrain conditions

A wide range of debris flow terrain conditions occurs within the study area, but two main basin types are recognized here based on sediment supply conditions. Transport-limited basins typically have a high density of headwater channels incised into thick glacial drift or closely jointed bedrock. This ensures a virtually unlimited debris supply in addition to many unstable trigger points for debris flows (Figure 2). Weathering-limited basins exhibit a lower frequency of events because of slower recharge rates and fewer zones of instability. This is usually due to more massive bedrock or a thinner cover of glacial drift (Figure 3). Of the 33 basins, 12 were classified as transport-limited and 21 as weathering-limited, based on air photograph interpretation and detailed field checking. Despite hazardous terrain conditions, all but two of the 33 upper basin areas were traversed on foot.

The implications of differing sediment supply conditions for debris flow activity are illustrated schematically in Figure 4. Debris flow frequency in transport-limited basins is controlled primarily by hydroclimatic events, since the supply of mobilizable sediment is rarely a limiting condition for debris flow occurrence. By contrast, weathering-limited basins require a significant recharge period prior to each debris flow event and exhibit a lower frequency of debris flow activity.

As a historical note, the distinction between transport- and weathering-limited conditions, first proposed in English by Carson and Kirkby (1972), has more distant roots in the work of Stiny (1910). He recognized two debris flow types, called 'Jungschutt Muren' (recent rubble debris flows) and 'Altschutt Muren' (old rubble debris flows). Stiny noted that old rubble debris flows '. . . occur more frequently than recent rubble debris

Figure 2. Stereopair of a typical transport-limited debris flow basin (No Good Creek). The basin is underlain by unstable Quaternary volcanic materials overlain by glacial drift and exhibits widespread slumping and ravelling. Mean debris flow frequency is 0·625 a^{-1} and debris flow activity averages 6300 $m^3 a^{-1}$

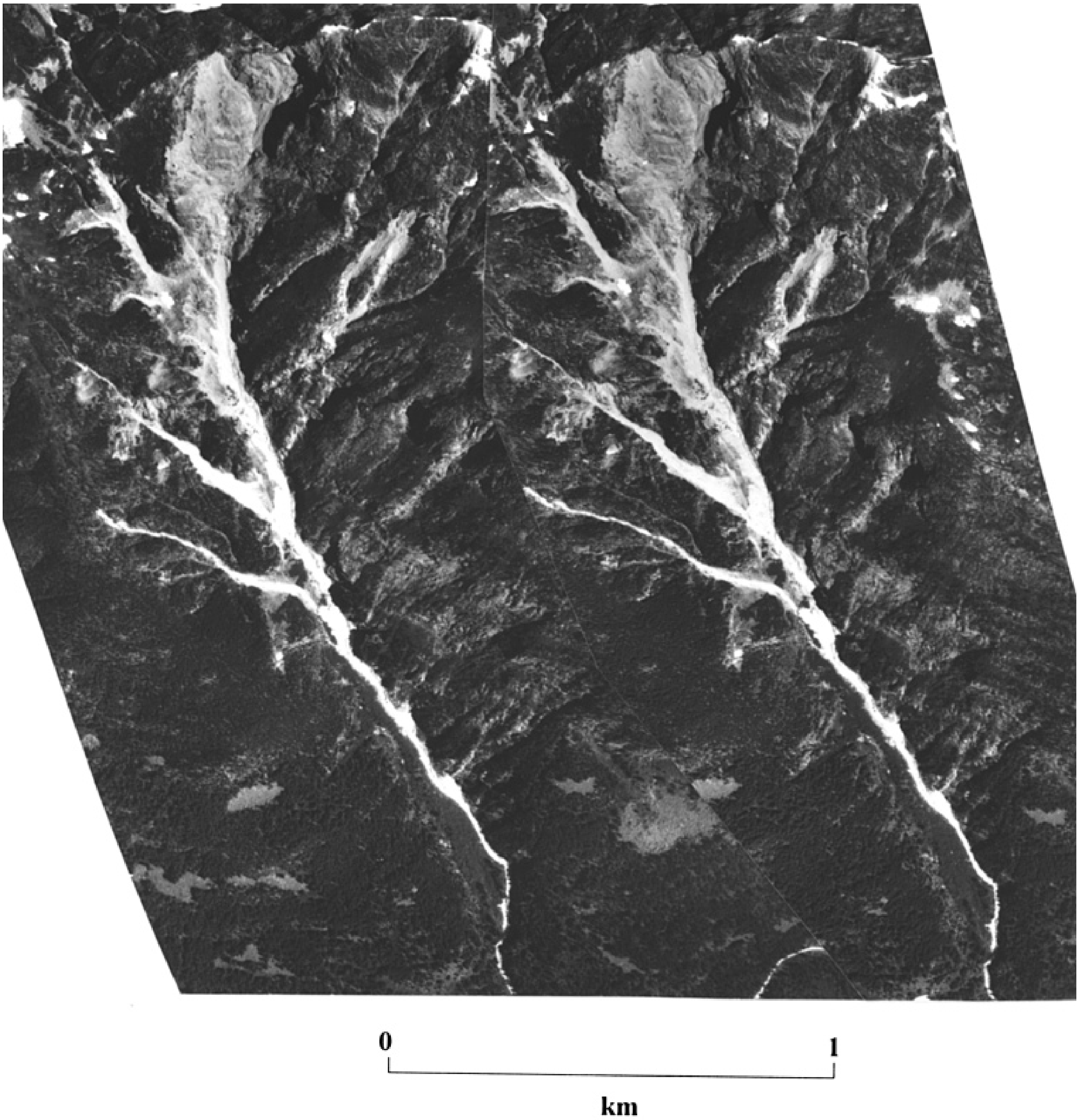

Figure 3. Stereopair of a typical weathering-limited debris flow basin (Clearwater Creek). The basin is underlain by massive quartz-diorite rock and has a thin, discontinuous drift cover. Mean debris flow frequency is 0·068 a^{-1} and debris flow activity averages 400 $m^3\ a^{-1}$

flows since there is always sufficient material readily available for debris transport' (Stiny, 1910; p. 74 in translation).

Debris flow activity within the study area

Significant differences in debris flow events occur between weathering- and transport-limited basins. A useful measure for comparison is debris flow activity, defined as the product of average event frequency and average event magnitude ($m^3\ a^{-1}$) Weathering-limited basins average 1300 $m^3\ a^{-1}$, or 280 $m^3\ km^{-2}\ a^{-1}$,

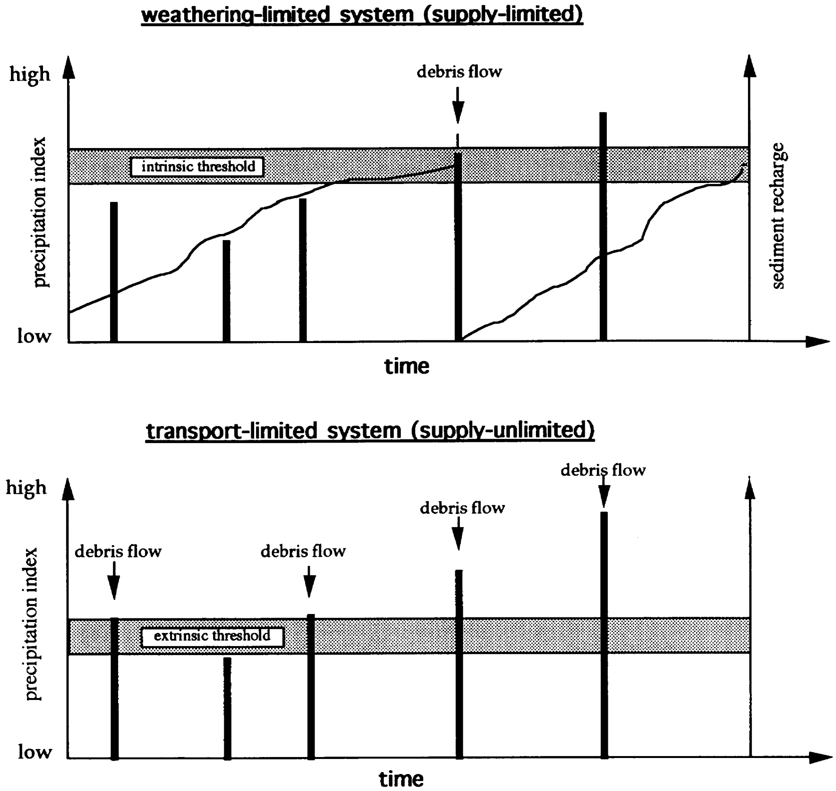

Figure 4. Weathering-limited and transport-limited concepts applied to the occurrence of debris flow events. Bars indicate precipitation, curved rising lines indicate cumulative sediment recharge

from a sample of 21 basins of mean area 4·6 km^2. Transport-limited basins average almost 8000 m^3 a^{-1}, or just over 2000 m^3 km^{-2} a^{-1} from a sample of 12 basins of average area 3·8 km^2. The largest individual events in the transport-limited group exceed 150 000 m^3, and are derived from highly unstable Quaternary volcanic centres at Mount Cayley and Meager Mountain (Figure 1). These data provide some impression of the huge sediment discharges, due to debris flows alone, derived from small basins in the more humid parts of the Canadian Cordillera.

METHODS

Debris flow frequency

Average debris flow frequencies for the 33 basins were determined principally by dating scarred trees and the time of onset of reaction wood caused by debris flow deposition. Over 800 wood samples were examined, including more than 100 complete discs cut from trees damaged or felled by debris flow impacts. These data were supplemented by air photograph records of recent debris flows and, in a limited number of cases, by historical and eyewitness reports. A total of 336 debris flow events was documented over the period 1770–1997; seven of the basins have records exceeding 150 years in length.

In most basins, a mean event frequency, f, was computed by dividing the number of recorded events by the total length of record (Table II). In cases where the date of the earliest event was documented by damage to a lone veteran tree, and the time gap between this event and the next oldest exceeded two standard deviations

Table II. Debris flow variables used in regression analysis

Variable	Description	Formula
Q_{max}	Debris flow peak discharge ($m^3\ s^{-1}$)	$A_{max}\ u$
M^*	Average debris flow magnitude (m^3)	$\sum M_i\ /\ N$
f	Average debris flow frequency (a^{-1})	$N\ /\ t$
I_A	Debris flow activity index ($m^3\ a^{-1}$)	$f\,M^*$

A_{max} = cross-sectional area at bouldery front of debris flow; M_i = magnitude of debris flow event; N = number of debris flow events recorded in a basin; t = length of debris flow record

about the mean return period, exclusive of this oldest event, the record was defined to begin with the second-oldest event.

Debris flow peak discharge

Debris flow lateral deposits along channel margins, as well as scarred trees, were used to reconstruct the maximum flow cross-sectional area, A_{max}, corresponding to the bouldery front of a debris flow. Cross-sectional measurements were preferably taken in bedrock or boulder-armoured channel reaches to avoid errors due to scour and fill of the channel following a debris flow event. Channels with notable bends provided data on mean flow velocity, u, according to the flow superelevation formula:

$$u = (gR_C \cos\beta \tan\alpha)^{0\cdot 5} \tag{1}$$

where g is gravitational acceleration, R_c is the radius of curvature of flow at the channel centre line, β is the channel longitudinal slope, and α the flow banking angle, measured from the elevation difference between lateral deposit crests in the channel bend. Flow peak discharge was then computed from $Q_{max} = A_{max}\ u$ (Table II).

Iverson *et al.* (1994) report that Equation 1 yields accurate velocity values in small-scale debris flow experiments, though the equation tends to overestimate velocity in sharp bends where waves and debris splashing tend to exaggerate superelevation. Accordingly, velocity and discharge estimates derived from this equation should be viewed as maxima. This is conservative in the context of engineering design.

Debris flow magnitude

Deposits from recent debris flows were surveyed to obtain estimates of total event volume. Volume was defined solely by the amount of debris flow material delivered to the basin's terminal fan, and thus excludes debris stranded within the upper channel. In several cases, fan deposits were severely eroded and reliable volume estimates could not be obtained. To work around this difficulty, a regression of peak discharge on volume was conducted using a compilation of local peak discharge–volume data from Hungr *et al.* (1984), VanDine (1985), Jordan (1994) and Jakob (1996) (Figure 5). Two fairly distinct data groups are seen in this figure, having significantly different slopes and intercepts. The groups correspond to granular and muddy debris flow types, a result similar to the findings of Mizuyama *et al.* (1992), who also identified muddy and granular types based on an examination of more than 250 Japanese and Chinese debris flows (Figure 5). The physical basis of the two groups seems to derive from the lesser strength of muddy flows, which usually show lower peak discharges relative to bouldery debris flows of the same total volume.

In our study area there is a general correspondence between debris flow type and basin type. Muddy debris flows are derived largely from transport-limited basins underlain by relatively weak volcanic and sedimentary rocks. Granular flows are typical of weathering-limited basins carved in more competent igneous intrusive rocks. The separation of granular and muddy events in Figure 5 led to the use of separate regression equations to estimate event volume from measured peak discharge.

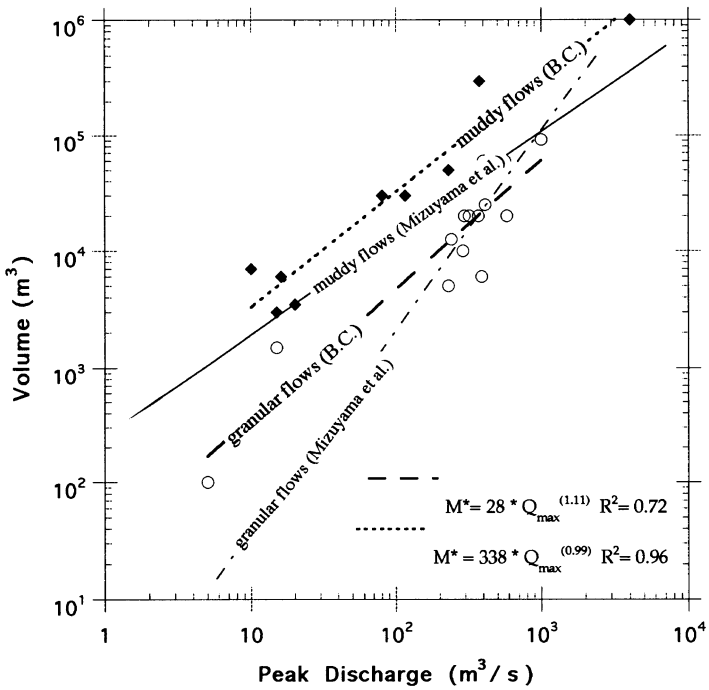

Figure 5. Relations between peak discharge and magnitude for British Columbian debris flows. Included for comparison are regressions for 'granular' and 'muddy' debris flow types computed by Mizuyama *et al.* (1992) from Japanese and Chinese data sets. Regression equations from Mizuyama *et al.* (1992): muddy flows, $M^* = 795\ Q_{max}^{0{\cdot}85}$, $R^2 = 0{\cdot}74$; granular flows, $M^* = 13\ Q_{max}^{1{\cdot}33}$, $R^2 = 0{\cdot}78$

Table III. Morphometric and sediment supply variables

Variable	Description	Formula
A_T	Total basin area (km^2)	
A_C	Area actively contributing debris (km^2)	
$A_{\%}$	Percentage area actively contributing debris	$A_C / A_T \times 100$
N_S	Weighted stability number	$\sum a_j \times W_j$
A_I	Active area index	$A_C \times N_S$
Z_T	Total basin relief (km)	$z_{max} - z_{min}$
Z_R	Elevation relief ratio	$(z^* - z_{min}) / (z_{max} - z_{min})$
D_d	Drainage density (km^{-1})	L_C / A_T
N_M	Melton's ruggedness number (km^{-2})	$D_d / A_T^{0{\cdot}5}$
R_0	Zero-order ruggedness	$1/k \sum (l_i / d_i)$
S	Mean basin slope (°)	
I_C	Rock compressive strength (kN m^{-2})	P/a_s

Definitions of terms: a_s = cross-sectional area of failure surface through point-load sample (m^2); a_j = proportion of total active area in stability class j; d_i = straight-line distance between intersections of a contour with the basin perimeter (m); k = number of contours surveyed to compute R_0; l_i = total length of contour between its intersections with the basin perimeter (m); L_C = total length of channels and debris chutes (km); j = number of ordinal terrain stability classes; P = applied point load on rock sample at failure (kN); W_j = stability weight in ordinal class j ($w_1 = 1$: $<$ 40 per cent of terrain polygon unvegetated and actively contributing debris, $w_2 = 2$: 40 –70 per cent of terrain polygon unvegetated and actively contributing debris, $w_3 = 4$: $>$ 70 per cent of terrain polygon unvegetated and actively contributing debris); z_{min} = minimum elevation in basin (m); z_{max} = maximum elevation in basin (m); z^* = mean elevation of basin (m)

Table IV. Results of discriminant function analysis

Variables	F value	d.f.	Signif.	λ
$A_{\%}$	19·9	32	0·001	0·62
N_s	10·6	31	0·001	0·46
D_d	3·8	30	0·060	0·41

Discriminant functions:
WL = $-1{\cdot}84 - 0{\cdot}05A\% + 3{\cdot}57N_s + 0{\cdot}99D_d$
TL = $-6{\cdot}51 + 0{\cdot}24A\% - 6{\cdot}32N_s + 0{\cdot}05D_d$

Terrain variables

Our choice of morphological and debris supply variables (Table III) was influenced partly by those used in earlier studies of debris flow terrain (Table I). To describe debris supply conditions, a raw measure of basin instability, termed debris contributing area, A_C, was divided by total basin area to yield a percentage active area, $A_{\%}$. A more refined measure of debris supply was area-weighted stability number, N_S, an index of basin stability based on three ordinal stability classes (Table III). N_S was based on a geometric progression of stability weights, in contrast to the arithmetic progression used in Jakob and Bovis (1996). A third variable, active area index, A_I, is defined as the product of N_S and A_C to provide the most sensitive measure of debris supply conditions.

Drainage density, D_d, is one of two indices used to describe basin roughness. An increase in degree of dissection means more area exposed to denudation, thereby increasing the amount of erodible sediment and the number of potential failure sites per unit basin area. Ruggedness number, R_0, considers contour sinuosity rather than channel network density (Table III). The elevation–relief ratio, proposed by Wood and Snell (1960), together with total basin relief, Z_T, provide measures of basin longitudinal profile and basin potential energy. Melton's ruggedness number, N_M, normalizes terrain relief by basin area and has proved to be a useful criterion for discriminating debris flow from non-debris flow basins (Jackson *et al.*, 1987). A measure of rock quality and its susceptibility to mechanical breakdown was provided by point-load testing (variable I_C Table III), using methods described in ISRM (1985). A total of 850 rock samples was tested, representing an average of 25 per basin.

RESULTS

Discriminant analysis

The initial subjective classification of basins as either weathering- or transport-limited, described earlier, was used as a framework for stepwise discriminant and regression analyses. Three statistically significant variables were identified in the discriminant analysis (Table IV). Retention of variables $A_{\%}$, N_s and D_d indicates that large, highly dissected debris-contributing areas currently provide the best criteria for discriminating transport-limited from weathering-limited basins. Equations below Table IV are discriminant functions for weathering- and transport-limited basins that correctly classify 30 of the 33 basins. The squared Mahalanobis' values indicate the distance of each basin from its respective group centroid, and provide numerical measures of basin misclassification (Table V).

Three misclassified cases were retained within their original groups based on a reassessment of the field and air photo evidence. McLeod Creek basin was retained in the transport-limited group since a large area of unstable talus occupies the upper part of the basin. Thus, debris supply conditions are not limiting in this basin, even though the percentage active area is significantly lower than the average for the transport-limited group. This case indicates that the spatial distribution of debris-contributing areas within a basin is an important factor, but is not described by any variable in the analysis presented here. Mount Currie and Kaboose Creek basins were retained in the weathering-limited group since most of their debris-contributing areas are underlain by bedrock, yielding debris at significantly lower rates than comparable unstable areas of

Table V. Mahalanobis' distance scores for debris flow basins

Weathering-limited basins	WL score	TL score	Transport-limited basins	WL score	TL score
Canyon	1·13	4·42	Boundary	2·73	0·80
Clearwater	13·46	18·61	Capricorn	9·93	1·96
Collis	0·84	7·07	Ferguson	3·80	0·66
Deepa	0·94	4·17	Fool's Gold	6·33	1·00
Endurance	0·94	8·43	Gunbarrel 1	9·58	8·38
Eureka	1·63	10·79	Gunbarrel 2	13·23	1·40
Howe	3·82	14·59	Gunbarrel 3	20·71	5·39
Kaboose	**8·18**	**4·27**	Hotsprings	2·51	1·38
Last Day	0·70	10·29	**McLeod**	**0·23**	**5·82**
Mt Currie	**2·85**	**2·56**	No Good	16·36	3·64
Nightmare	2·06	8·57	Pothole	7·98	1·05
Nineteen Mile	1·34	12·00	Turbid	9·48	1·24
No Law	0·93	4·64			
Patterson	1·95	10·55			
Peterson	0·80	8·57			
Rainy	0·66	7·17			
Rogers	0·25	6·17			
Snake	0·72	9·06			
Terminal	0·99	5·20			
Two Mile	1·19	6·53			
Wildcat	1·14	10·54			
Means:	2·22	8·30	Means:	8·57	2·72

Basins in bold are misclassified. For a discussion of these cases see text.

either glacial drift or colluvium. These three cases indicate that both the vertical distribution of active areas within the basin, and the degree of bedrock control within these areas, need to be given adequate weighting in future studies.

Regression analysis

The purpose of the regression analysis was to develop prediction equations for debris flow magnitude, M^*, peak discharge, Q_{max}, frequency, f, and activity index, I_A, using the terrain variables described in Table III. Univariate regressions (Table VI) yielded only two instances of explained variance exceeding 50 per cent. Accordingly, multivariate models were then examined using forward-stepwise regression (Dillon and Goldstein, 1984). Separate regressions were run for the weathering-limited and transport-limited subgroups as well as for the unstratified sample of 33 basins. In each case, a maximum of two terrain predictor variables

Table VI. R^2 statistics for univariate and multivariate (MV) models

	A_C	$A_\%$	A_I	A_T	D_d	I_C	L_C	N_M	N_S	R_0	S	Z_R	Z_T	MV
f												**0·18**		**0·76**
Q_{max}	0·40		0·37	0·25	0·23		0·37			0·18			**0·59**	**0·76**
M^*	0·52		**0·67**	0·18			0·46			0·22			0·25	**0·91**
I_A	0·22		**0·28**	0·10			0·24			0·25		0·12	0·20	**0·80**

Right-hand column gives the best results obtained from multivariate (*MV*) models on stratified data sets. Other entries give univariate regression results using unstratified data. Best estimates are shown in bold face. Blank cells indicate that $R^2 < 0{\cdot}1$

Table VII. Regression results for stratified and unstratified data sets

Regression equations	R^2	R^{2*}	F ratio	Signif.	Mean Pred/ Obs
Unstratified sample ($n = 33$)					
$M^* = 800\ Z_T^{2.38}\ A_I^{1.15}$	0·73	0·72	41·0	0·001	0·99
$Q_{max} = 40\ Z_T^{2.55}\ A_I^{0.35}$	0·70	0·69	34·5	0·001	1·10
$I_A = 190\ Z_T^{2.28}\ A_I^{1.20}$	0·59	0·58	21·8	0·001	0·91
f No usable relation	<0·40				
Weathering-limited sample ($n = 21$)					
$\log M^* = 0.48 + 2.00\ Z_T + 0.10\ A_{\%}$	0·75	0·74	29·0	0·001	1·00
$\log Q_{max} = -0.77 + 1.66\ Z_T + 0.30\ A_{\%}$	0·75	0·74	27·4	0·001	1·10
$I_A = 850\ Z_T^{3.30}\ A_I^{0.07}$	0·51	0·48	9·3	0·005	1·09
f No usable relation	<0·40				
Transport-limited sample ($n = 12$)					
$M^* = 420\ A_I^{0.82}\ N_S^{2.55}$	0·91	0·90	46·7	0·001	1·08
$Q_{max} = 40\ A_I^{0.72}\ N_S^{0.40}$	0·76	0·74	14·0	0·001	1·10
$I_A = 300\ R_0^{2.95}\ Z_R^{-2.75}$	0·80	0·78	18·4	0·001	1·10
$f = 0.01\ R_0^{1.06}\ Z_R^{-3.50}$	0·76	0·74	14·6	0·005	1·10

R^2 is the coefficient of determination. R^{2*} is the adjusted coefficient of determination, computed from: $R^{2*} = 1 - (1 - R^2)\ (n - 1) / (n - p)$, where n is sample size and p is number of model parameters.

was used to ensure an appropriate ratio of cases to variables (Table VII). Least-squares regression coefficients obtained from the stepwise regression model were then adjusted in a spreadsheet 'solver' to ensure that the ratio of mean observed to mean predicted values lay between 0·9 and 1·1. In addition, graphical monitoring of solver solutions ensured that the model was fitting well throughout the full range of values.

In many cases, the logarithms of M^*, Q_{max}, I_A and f correlated best with the logarithms of terrain variables; power-law models were fitted to these cases (Table VII). In other cases, semi-logarithmic regression models were used. In the weathering-limited group, predictor variables for magnitude and Q_{max} are similar to those identified in the unstratified data set, since two-thirds of the total group are weathering-limited basins. Within the unstratified data set, magnitude, M^*, peak discharge, Q_{max}, and activity index, I_A, are best predicted by a combination of basin relief, Z_T, and active area index, A_I. The product of these terms represents a surrogate for the potential energy of erodible material within a basin.

In transport-limited basins, M^* and Q_{max} are best predicted by active area index, A_I, as well as weighted stability number, N_S. Debris flow activity, I_A, is best predicted by zero-order drainage density, R_0, and the hypsometric index, Z_R. Ruggedness indicates both the effectiveness of debris delivery and the volume of sediment available, and therefore is a good index of a basin's geomorphic activity. Variable Z_R describes basin longitudinal profile and may control how much of the mobilized sediment reaches the basin fan. (As noted above, flow volumes in this study were defined solely by material delivered to the fan.) Debris flow frequency, f, is reasonably well predicted in transport-limited basins by a two-variable model (R_0 and Z_R). Again, ruggedness serves as a surrogate for basin instability and emphasizes that highly dissected basins are more prone to generating debris flows during extreme climatic events. No acceptable prediction of frequency was obtained in either the unstratified or the weathering-limited groups.

The values of exponents in the regression models are largely artefacts of the units of measurement chosen. For example, basin relief, Z_T, typically has exponent values between 2 and 3. However, if relief were re-expressed in units consistent with those of M^* and Q_{max} (i.e. metres, not kilometres), values would be of the order 10^{-3}. To avoid cumbersome decimals in regression coefficients, basin relief was expressed in kilometres.

Table VIII. Regression results from independent test basins

Variable	N	R^2	F value	Signif.	Predicted /observed
M^*	11	0·70	9·4	0·03	1·14
Q_{max}	11	0·54	4·8	0·05	1·00
I_A	11	0·56	5·1	0·05	3·36

The regression results significantly extend the initial findings reported in Jakob and Bovis (1996) since three years of additional field data are incorporated in the analysis reported here. These new data explain the differences in both the variables selected and the coefficient values between the two studies. Furthermore, basin classifications in the present study are based on debris supply conditions, whereas classification in our earlier study was based on basin lithology (granitic versus non-granitic).

Independent test of the regression equations

Regression equations were tested using an independent sample of 12 basins, having a known history of debris flow events, and having terrain attributes similar to those of the original sample basins. Most test basins are located along the east shore of Howe Sound fjord, where a series of fatal debris flow disasters occurred along Highway 99 in the early 1980s. Debris flow event data were compiled principally from Thurber Engineering Ltd (1983), who conducted detailed field and air photograph observations, supplemented with newspaper archives and eye-witness accounts (Figure 1). One of the 12 test basins (Ted Creek) was discarded because of logging and road construction disturbances in the upper watershed. Relative to its basin size, both the peak discharge and total volume values in Ted Creek were notably higher than those of the other test basins, confirming the well established influence of such disturbances on debris flow activity (Sidle *et al.*, 1985).

Using the discriminant functions from the original data set, nine of the 11 test basins were classed as weathering-limited, two as transport-limited. Given these small sample sizes, no attempt was made to partition the total sample of 11 basins into separate regression predictor groups. The results in Table VIII are therefore based on the unstratified equations in Table VII, applied to both magnitude and peak discharge. Overall, the results of the tests are encouraging, though a notable deviation from the line of equal values is noted in the activity index regression.

DISCUSSION

The regression results indicate that prediction of some debris flow attributes is possible with only two terms (involving three variables, since A_I is the product of A_C and N_S). Especially good results were obtained for magnitude and peak discharge. Prediction of debris flow frequency and activity index remains problematical, except in the geomorphically more active transport-limited basins. In weathering-limited basins, poorer predictions for frequency and activity stem from the fact that several very large debris flows have been triggered by new zones of instability occurring unexpectedly within formerly stable, well forested terrain. Such behaviour implies progressive weakening of slopes by weathering and basal sapping and is not

Table IX. Pearson correlations between terrain variables and debris flow events

Basin group	Terrain variable	Max.volume	Mean volume	Max. peak discharge	Mean peak discharge
Transport-limited	A_I	0·76	0·75	0·87	0·90
Weathering-limited	Z_T	0·82	0·83	0·83	0·77

predictable by our methods. This is a concern given the relatively large number of weathering-limited basins within the study area.

In this study, mean magnitude values have been predicted since, in a geomorphic context, the annual average sediment delivery is of most relevance to topics such as sediment budgets and fluvial adjustments to hillslope processes. In engineering applications, however, maximum magnitudes are of greater significance in the design of debris flow retention and control structures. Table IX gives univariate correlation coefficients between terrain variables and extreme event values. Included for comparison are the best univariate correlations between mean event values and terrain variables. The results suggest there are good prospects for predicting both extreme event magnitudes and mean magnitudes from terrain variables.

Some of our terrain variables yield results similar to those obtained in previous studies of debris flow terrain. Jackson *et al.* (1987) found that debris flow basins in the Canadian Rockies had Melton's ruggedness values of 0·3–1·5, with alluvial basin values generally below 0·3. In our study, the mean ruggedness value is 1·01 (standard deviation of 0·46), with a minimum value of 0·53. This confirms the utility of Melton's ruggedness number in the process-typing of small basins.

Several studies listed in Table I have found usable relations between magnitude and either basin area, A_T, or channel length, L. In our study, A_T and L correlate well with peak discharge ($R^2 = 0{\cdot}86$ and 0·84, respectively), but only within the transport-limited group. However, both A_T and L are out-performed by active area index, A_I, within this same basin group. In the weathering-limited basin group, neither A_T nor L correlate significantly with any of the debris flow variables.

Important negative results encountered in the analysis are the very weak correlations between area-normalized debris flow attributes (volume ($m^3\ km^{-2}$), peak discharge ($m^3\ s^{-1}\ km^{-2}$) and activity index ($m^3\ a^{-1}\ km^{-2}$)) and terrain variables. This indicates a scale effect, in that many variables describing basin activity are also correlated with basin size, implying a greater chance of encountering unstable zones in larger basins. Size is also correlated with basin relief, which in turn is related to steeper topography at the higher elevations. There also occurs a lesser stabilization of slopes by vegetation as timberline is approached. In addition, the highest relief areas contain unstable Neoglacial material above timberline.

The independent test of the regression equations using 11 test basins yielded fairly good results, despite the fact that data quality in many of them is somewhat lower than in the original basin sample. This may account for our inability to predict either debris flow frequency or activity index within the test sample. Limited data on frequency are available since most of the test basin fans were logged about 50 years ago, thereby removing much of the usable dendrochronological evidence. Highway 99 north of Vancouver was only completed in the late 1950s, and historical recording of debris flows began only about 30 years ago when development of the debris fans commenced. As a result, only the largest and most destructive events have been recorded, hence estimates of both magnitude and frequency are likely to be very biased.

A final comment is in order concerning the representativeness of our original sample of 33 basins. As noted earlier, debris flow basins were deliberately selected to maximize the quality of dendrochronological evidence of past debris flow activity. Many other basins had to be discarded because of the confounding influence of snow avalanches scarring trees in the zone of debris flow deposition. Secondly, relatively active basins were selected to ensure an adequate number of events within the time frame of the dendrochronological record. Thus, the sample is considered representative of basins with relatively high debris flow frequencies whose fans are largely unaffected by snow avalanche impact.

CONCLUSIONS

Multiple regression methods are used to predict debris flow attributes from terrain variables. Predictor variables include morphometric indices, some of which have been used in previous debris flow studies, in addition to new variables describing debris supply conditions. The sample of basins was stratified into weathering-limited and transport-limited subtypes, and separate regression equations were used to predict debris flow attributes in each group. Stratification based on debris supply conditions notably improved the regression results. Acceptable predictions for magnitude, peak discharge, frequency, and debris flow activity (frequency times magnitude) were obtained from regression models containing only two predictor variables.

However, prediction of debris flow frequency and activity was not successful within the unstratified and weathering-limited basin groups.

To improve confidence in the regression and discriminant functions, a high priority is periodic monitoring of the basins for new debris flow events. We are conducting annual resurveys of fans in the 45 basins to improve the quality of the existing data set, and ultimately the performance of the models. In addition, debris flow events in basins not included in the original sample are being added to the peak discharge–volume relations to provide more accurate estimates of magnitude from measured peak discharge.

ACKNOWLEDGEMENTS

Funding for the fieldwork was provided by grants to M.J. Bovis from the Natural Sciences and Engineering Research Council of Canada. Living expenses for M. Jakob were covered by a scholarship from the Gottlieb Daimler und Karl Benz Stiftung. Field assistance was provided by Drew Brayshaw, Elizabeth Bronson, Noel Castree, Ernst Jakob, Katherine McLeod, Steven Rice, Deepa Spaeth and Scott Weston. We also thank Dr S.G. Evans, Geological Survey of Canada, for assistance in helicopter access to three of the basins.

REFERENCES

Caine, N. 1980. 'The rainfall intensity-duration control of shallow landslides and debris flows', *Geografiska Annaler*, **62A**, 23–27.

Cannon, S. H. and Ellen, S. D. 1988. 'Rainfall that resulted in abundant debris flow activity during the storm', in Landslides, Floods, and Marine Effects of the Storm of January 3–5, 1982, in the San Francisco Bay Region, California US Geological Survey, Professional Paper 1434, 27–34.

Carson, M. A. and Kirkby, M. J. 1972. Hillslope Form and Process, Cambridge University Press, Cambridge.

Church, M. and Miles, M. J. 1987. 'Meteorological antecedents to debris flow in southwestern British Columbia in Costa, J. E. and Wieczorek G. F. (Eds), Debris Flows/Avalanches: Process, Recognition and Mitigation, Geological Society of America, Reviews in Engineering Geology VII, 63–79.

Dillon, W. R. and Goldstein, M. 1984. Multivariate Analysis–Methods and Applications, John Wiley & Sons, New York.

Ellen, S. D. and Mark, R. K. 1993. 'Mapping debris flow hazard in Honolulu using a DEM', Hydraulic Engineering '93, Proceedings, 2, 1774–1779.

Evans, S. G. and Savigny, K. W. 1994 'Landslides in the Vancouver–Fraser Valley–Whistler region', in Monger, J. W. H. (Ed.), Geology and Geological Hazards of the Vancouver Region, Southwestern British Columbia, Geological Survey of Canada Bulletin 481, 251–286.

Fannin, R. J. and Rollerson, T. P. 1993. 'Debris flows: some physical characteristics and behaviour', *Canadian Geotechnical Journal*, **30**, 71–81.

Hampel, R. 1977. 'Geschiebewirtschaft in Wildbächen', *Zeitschrift des Vereins der Diplomingenieure der Wildbach und Lawinenverbauung sterreichs*, **4**, 53–144.

Hungr, O., Morgan, G. C. and Kellerhals, R. 1984. 'Quantitative analysis of debris torrent hazards for design of remedial measures', *Canadian Geotechnical Journal*, **21**, 663–677.

Ikeya, H. 1981. 'A method of designation for areas in danger of debris flow', in Erosion and sediment transport in Pacific Rim steeplands, International Association of Hydrological Sciences, Christchurch, New Zealand, Publication **132**, 576–587.

Ikeya, H. and Mizuyama, T. 1982. Flow and deposit properties of debris flow, Public Works Research Institute, Tsukuba, Japan, Report 157–2, 88–153.

ISRM (International Society of Rock Mechanics, Commission on Testing Methods), 1985. 'Suggested method for determining point load strength', *International Journal of Rock Mechanics, Mining Science, and Geomechanical Abstracts*, **22**, 53–60.

Iverson, R. M. 1997. 'The physics of debris flows', *Reviews of Geophysics*, **35**, 245–296.

Iverson, R. M., LaHusen, R. G., Major, J. J. and Zimmerman, C. L. 1994. 'Debris flow against obstacles and bends: dynamics and deposits', Abstract of poster presentation, Fall Meeting, American Geophysical Union.

Jackson, L. E., Kostaschuk, R. A. and MacDonald, G. M. 1987. 'Identification of debris flow hazard on alluvial fans in the Canadian Rocky Mountains', in Costa, J. E. and Wieczorek, G. F. (Eds), Debris Flows/Avalanches: Process, Recognition, and Mitigation, Geological Society of America, Reviews in Engineering Geology, VII, 115–124.

Jakob, M. 1996. Morphometric and geotechnical controls of debris flow frequency and magnitude in southwestern British Columbia, unpublished PhD thesis, University of British Columbia.

Jakob, M. and Bovis, M. J. 1996. 'Morphometrical and geotechnical controls of debris flow activity, southern Coast Mountains, British Columbia, Canada', *Zeitschrift für Geomorphologie Supplementband*, **104**, 13–26.

Jakob, M., Hungr, O. and Thomson, B. 1997. 'Two debris flows with anomalously high magnitude', in Chen, C. (Ed.), Debris-flow Hazards Mitigation: Mechanics, Prediction, and Assessment. Proceedings of First International Conference, American Society of Civil Engineers, 382–394.

Johnson, P. A., McCuen, R. H. and Hromadka, T. V. 1990. 'Magnitude and frequency of debris flows', *Journal of Hydrology*, **123**, 69–82.

Jordan, P. 1994. Debris flows in the southern Coast Mountains, British Columbia: Dynamic behaviour and physical properties, unpublished PhD thesis, University of British Columbia.

Keefer, D. K., Wilson, R. C., Mark, R. K., Brabb, E. E., Brown, W. M., Ellen, S. D., Harp, E. L., Wieczorek, G. F., Alger, C. S. and

Zatkin, R. S. 1987. 'Real-time landslide warning during heavy rainfall', *Science*, **238**, 921–925.
Kronfellner-Kraus, G. 1983. 'Torrent erosion and its control in Europe and some research activities in the field in Austria', SABO - The Erosion-Control Engineering Society Japan, 3, 33–44.
Mizuyama, T. 1982. 'Analysis of sediment yield and transport data for erosion and control works', in Recent Development in the Explanation and Prediction of Erosion and Sediment Yield, Proceedings of Exeter Symposium, International Association of Hydraulics Research, 137, 177–182.
Mizuyama, T., Kobashi, S. and Ou, G. 1992. 'Prediction of debris flow peak discharge', Interpraevent, International Symposium, Bern, Switzerland, Tagespublikation, 4, 99–108.
Monger, J. W. H. (Ed.) 1994. Geology and Geological Hazards of the Vancouver Region, southwestern British Columbia, Geological Survey of Canada Bulletin 481.
Monger, J. W. H. and Journeay, J. M. 1994. Geology and crustal structure of the southern Coast and Intermontane Belts, southern Canadian Cordillera, British Columbia, Geological Survey of Canada, Open File 2490.
Ryder, J. M. 1981. 'Geomorphology of the southern part of the Coast Mountains of British Columbia', *Zeitschrift für Geomorphologie*, **37**, 120–147.
Sidle, R. C., Pearce, A. J. and O'Loughlin, C. L. 1985. Hillslope Stability and Land Use, American Geophysical Union, Water Resources Monograph **11**.
Stiny, J. 1910. 'Die Muren,' Versuch einer Monographie mit besonderer Berücksichtigung der Verhältnisse in den Tiroler Alpen, Innsbruck, Verlag der Wagnerschen Universitäts-Buchhandlung, translated by M. Jakob and N. A. Skermer, (1997).
Swanston, D. N. and Swanson, F. J. 1976. 'Timber harvesting, mass erosion, and steepland forest geomorphology in the Pacific Northwest', in Coates, D. R. (Ed.), Geomorphology and Engineering, Dowden, Hutchinson, and Ross, Stroudsburgh, Penn. 199–221.
Takahashi, T. 1981. 'Estimation of potential debris flows and their hazardous zones: soft countermeasures for a disaster', *Journal of Natural Disaster Science*, **3**, 57–89.
Thurber Engineering Ltd. 1983. Debris torrent and flooding hazards, Highway 99, Howe Sound, Report to Ministry of Transportation and Highways, British Columbia, Vancouver.
VanDine, D. F. 1985. 'Debris flows and debris torrents in the southern Canadian Cordillera', *Canadian Geotechnical Journal*, **22**, 44–67.
Wood, W. F. and Snell, J. B. 1960. A quantitative system for classifying landforms, Quatermaster Research and Engineering Center, US Army, Technical Report EP-124.

